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THE NATURE OF THE ANOMALOUSLY HIGH PHOTOVOLTAGES (AHP-EFFECT) IN SEMICONDUCTOR FILMS

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ABSTRACT

The mechanism of the AHP effect in semiconductor films is analyzed. The experiments show that the AHP effect in Ge, Si, and GaAs films is caused by a photodiffusion mechanism, and by micro-*p*-*n* junctions in CdTe films.

1. Numerous reports of various types (Ref. 1 - 20) have been recently /1037* devoted to the effect of anomalously high photovoltages (AHP-effect) in semiconductor films. However, up to the present the theory of the AHP-effect has remained at the level of more or less authentic hypotheses. The following diagram presents the total group of these hypotheses in a systematized form which readily lends itself to an examination:

AHP-Effect

- Microphoto-battery (Ref. 17)
  - Outer Photoeffect (Ref. 21)
  - Dember-Effect (Ref. 3, 21)
  - *p*-*n*-Junctions (Ref. 8, 21)
    - Potential Barriers at the Grain Boundaries (Ref. 1, 5)
    - Packing Defects at the Phase Boundaries (Ref. 4, 7)
- Photocell (Ref. 15)
  - Gradient of Collector Concentration (Ref. 15)

The theoretical investigation and the direct experiments performed in (Ref. 17) have made it possible to significantly narrow down the range of possibilities among which the physical cause of the AHP-effect may be found.

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* Numbers in the margin indicate pagination in the original foreign text.

This report indicated the untenable nature of the concepts and computations of Brandhorst and Potter (Ref. 15), who attempted to regard AHP-films as single photocells with a complex distribution of the capture levels. The theory regarding the multi-element ("battery") nature of the AHP-effect was substantiated. In addition, it was shown experimentally that the AHP-effect is not related to the outer photoeffect.

As a result, the problem of the nature of the elementary processes lying at the basis of the AHP-effect is reduced to a dilemma -- either the photovoltaic effect in microscopic *p-n* junctions, or the diffusion (Dember) effect in micro-regions which are uniform in their type of conductivity. As may be seen from the diagram presented above, the models based on the concepts of potential barriers at the boundaries of phases, grains, etc., do not differ in principle from the system of *p-n* junctions, and they must be regarded as definite concrete expressions of the *p-n* junction hypothesis.

2. Figure 1 schematically shows the structure of an AHP-film corresponding to the *p-n* junction (a) and the Dember (b) models. In the first model, the high-voltage photovoltage V_{AHP} results from summation of elementary photovoltages generated at junctions of one type (for example, *p-n*), since junctions of another type (*n-p*) are not illuminated (see Figure 1a):

$$V_{AHP}=\frac{kT}{q}\sum_{i=1}^{N}\ln\left(1+\frac{J_{fi}}{J_{si}}\right)=\frac{kT}{q}\ln\prod_{i=1}^{N}\left(1+\frac{J_{fi}}{J_{si}}\right)=N\frac{kT}{q}\ln\left[1+\widetilde{\left(\frac{J_{fi}}{J_{si}}\right)}\right]. \quad (1)$$

Here J_{si} and J_{fi} represent the saturation current and the photocurrent at the i^{th} *p-n* junction. /1038

The Dember model (Figure 1b) consists of photoconductive regions which are divided by layers impeding the exchange of free carriers between these photoconductive regions. In this case, we have

$$V_{AHP}=\frac{kT}{q}\frac{b-1}{b+1}\sum_{i=1}^{N}\ln\frac{\sigma_{2i}}{\sigma_{1i}}=\frac{kT}{q}\frac{b-1}{b+1}\ln\prod_{i=1}^{N}\frac{\sigma_{2i}}{\sigma_{1i}}= \quad (2)$$
$$=N\frac{kT}{q}\frac{b-1}{b+1}\ln\widetilde{\left(\frac{\sigma_{2i}}{\sigma_{1i}}\right)}.$$

Here $\sigma_{1i} = \sigma_0 + \Delta\sigma_{1i}$ and $\sigma_{2i} = \sigma_0 + \Delta\sigma_{2i}$ represent the values of the total conductivity (dark plus photo) on the left and right boundaries, respectively, of the i^{th} micro-region.

We should note that in the Dember model of the AHP-effect, the layers between the photoconductive regions may be both high- and low-ohmic layers.

3. If we investigate all of the known experimental facts, from the point of view of the dilemma regarding the nature of the elementary processes lying at the basis of the AHP-effect, we find that many characteristics are

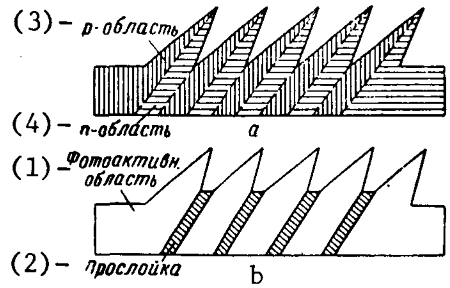

Figure 1

Model of AHP-Film: a - Of Micro-p-n Junctions; b - Of Photodiffusion Micro-regions

(1) - Photoactive region; (2) - Layer; (3) - p-region; (4) - n-region.

not critical for solving it. For example, let us investigate sign inversion of V_{AHP} when the AHP-films are illuminated by long-wave light, instead of by short-wave light (see, for example [Ref. 6]). When viewed from the p-n junction hypothesis, this may be explained by the fact that long-wave light which penetrates deeply produces non-equilibrium carriers not only at the p-n junctions, but also at the n-p junctions (see Figure 1a). This may also be explained by the fact that an increase in λ must lead to attenuation of the AHP-effect and, if the n-p junctions are sufficiently effective, it must lead to sign inversion of V_{AHP}.

For the photodiffusion model (see Figure 1b), sign inversion of V_{AHP} when λ increases may be explained by the concept of the anomalous Dember effect (Ref. 22). When surface recombination occurs at a fast rate on the illuminated grain, the photodiffusion current in the Dember element changes its sign when a change is made from short-wave light to long-wave light.

4. A physical discussion of the dependence of V_{AHP} on the light intensity may lead to more concise conclusions. Let us examine the expression for photovoltages produced by photovoltaic and photodiffusion cells.

$$v_{p-n} = \frac{kT}{q}\ln\left(1+\frac{J_f}{J_s}\right), \qquad v_{\text{Demb}} = \frac{kT}{q}\frac{b-1}{b+1}\ln\frac{1-\Delta\sigma_2/\sigma_0}{1+\Delta\sigma_1/\sigma_0}. \tag{3}$$

The linearity of the lux-volt characteristics is disturbed during the photodiffusion effect when the photoconductivity becomes commensurable with the dark conductivity: /1039

$$\Delta\sigma \equiv q\mu(1+b)\Delta n \sim \sigma_0 \equiv q\mu n_{\text{basic}} \tag{4}$$

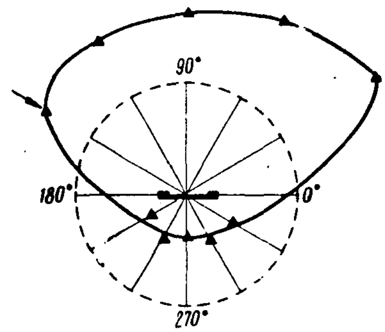

Figure 2

Dependence of V_{AHP} on the Illumination Angle for Germanium AHP-Films

i.e., when $\Delta n \sim n_{bas.}$*. When there is a photovoltaic effect at the *p-n* junction, the linearity of the lux-volt characteristics is disturbed for

$$J_f \equiv qD\,\Delta n\,/\,L \sim J_s \equiv qDn_{nonbas.}/L, \tag{5}$$

i.e., when $\Delta n \sim n_{nonbas.}$.

It may be seen from (4) and (5) that, in the case of photovoltaic microphotocells, the linearity of lux-volt characteristics must be disturbed much earlier than in the case when the film consists of photodiffusion microregions.

Turning to Figure 1a, presented in (Ref. 12), we may see that the AHP-films of Si, Ge and GaAs have linear, or almost linear, lux-volt characteristics up to I = 300,000 lux, since there is sharp non-linearity even for I = 20,000 lux in the AHP-films of CdTe. This leads one to think that the AHP-effect in Si, Ge and GaAs is caused by a photodiffusion mechanism, and is caused by the formation of photovoltages at the *p-n* junctions in CdTe.

However, we may reach a final conclusion regarding the mechanism of the AHP-effect by analyzing the lux-volt characteristics only by independent measurements of $n_{bas.}$, since $n_{bas.}$ may differ by several orders of magnitude in the films of different material.

5. It is our opinion that the study of the dependence of the magnitude and sign of V_{AHP} on the light angle of incidence represents a critical experiment for solving the problem of the nature of the physical processes in AHP-films.

* *Bas.* denotes basic.

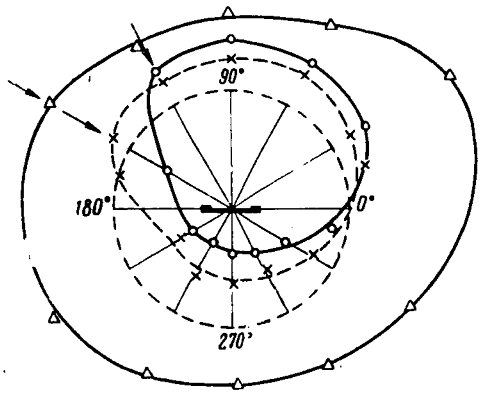

Figure 3

Dependence of V_{AHP} on the Illumination Angle for Gallium Arsenide AHP-Films

If the AHP-effect is caused by summation of the photovoltages at the electron-hole junctions, then a change in the angle at which the film is illuminated between 0 - 180° cannot lead to sign inversion of V_{AHP}, since at any light angle of incidence the *p-n* junctions will be illuminated more readily than the *n-p* junctions (see Figure 1a). The sign of V_{AHP} can change only when the film is illuminated at angles which are larger than 180°. If the AHP-effect is caused by the Dember mechanism, we would expect that the direction at which the depositing of the AHP-film occurs may correspond to the sign inversion of V_{AHP}, since -- when the illumination changes from one grain of the AHP-film micro-element to another -- with a normal Dember effect the diffusion direction of the curve carriers which are produced by the light changes, and consequently the sign of the V_{AHP}. With an anomalous Dember effect -- i.e., if the rate of surface recombination is much greater at one of the micro-element grains than it is at another -- the photodiffusion direction will be independent of the illumination direction, i.e., sign inversion of V_{AHP} must not occur when the light angle of incidence is changed by the angle at which the film is deposited.

It follows from the study presented above that the sign inversion of V_{AHP} between the illumination angles of 0 - 180° definitely points to the photodiffusion (Dember) mechanism of the AHP-effect, whereas the lack of inversion makes it impossible to reach a definite conclusion.

6. Figures 2, 3, and 4 employ polar coordinates to present the results derived from experiments measuring the angular dependences of V_{AHP} for Ge, GaAs and CdTe films.

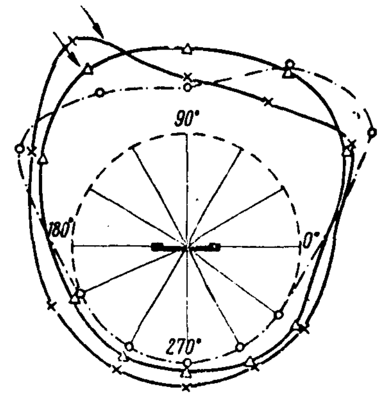

Figure 4

Dependence of V_{AHP} on the Illumination Angle for Cadmium Telluride AHP-Films

The dependence of the film illumination on the light angle of incidence was computed by a cosine law. The measured values of the photovoltages were normalized to unit illumination. The dotted circle in the figures designates the zero level of V_{AHP}. The passage of the experimental curve through the dotted curve corresponds to a change in the sign of V_{AHP}. The values of V_{AHP} are plotted radially in relative units. The arrows indicate the directions in which the AHP-films were deposited.

The experimental polar diagrams of $V_{AHP}(\phi)$ for Ge and GaAs films indi- /1040
cate that for the majority of samples, sign inversion of V_{AHP} occurs for illumination angles which are close to the film depositing angles (see Figures 2 and 3). Similar results were obtained for Si AHP-films. On the other hand, no sign inversion of V_{AHP} was observed in any of the 30 CdTe films which were studied. Typical diagrams of $V_{AHP}(\phi)$ for CdTe are shown in Figure 4.

These experiments show that the AHP-effect in Ge, Si and GaAs films is caused by a photodiffusion mechanism, and by micro-p-n junctions in CdTe films.

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